APODIZED FIBER BRAGG GRATING AND IMPROVED PHASE MASK, METHOD AND SYSTEM FOR MAKING THE SAME

FIELD OF THE INVENTION

5 The present invention relates to Fiber Bragg gratings (FBGs), and more particularly concerns a phase mask, a method and a system for facilitating the fabrication of apodized FBGs.

BACKGROUND OF THE INVENTION

10 A fiber Bragg grating is a refractive index modulation having a periodic profile, photoinduced in an optical fiber. Writing a FBG comprises two aspects: phase and amplitude. The phase gives the position of the FBG index fringes relative to the assumed underlying uniform pitch, and the amplitude is the magnitude of the index modulation at any given location in the FBG. Variation of the FBG amplitude is

15 often called apodization, since the ends of the FBG must be softened (apodized, or gradually reduced to zero) in order to avoid undesirable group delay and reflectivity ripples, which would result from an abrupt transition from a non-zero amplitude to zero.

20 To mathematically describe the FBG, the modulation of the effective refractive index of a single mode fiber can be written as:

$$n(x) = n_{eff}(x) + \Delta n(x)\cos(k_{g0}x + \phi_g(x)) = n_{eff}(x) + \text{Re}\{\Delta n(x)\exp[i(k_{g0}x + \phi_g(x))]\}$$

(1)

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where the FBG central k-vector is k_{g0} = $2\pi/\Lambda_g$ and Λ_g is the central period (or pitch) of the grating in the fiber. This index modulation causes a Bragg reflection band at a desired central wavelength λ_B, which is given by $\lambda_B = 2n_{eff}\Lambda_g$, and where n_{eff} is the effective average (i.e. excluding the rapidly varying index modulation) mode index of the single mode fiber. n_{eff} can be slowly varying and thus it is written in Eq. (1)

30 as $n_{eff}(x)$. $\Delta n(x)$ is the amplitude of the index modulation, and therefore represents

the apodization profile. $\phi_g(x)$ is the residual phase, representing the fringe position relative to the uniform period Λ_g, 2π of phase corresponding to a fringe position shift equal to the full fringe period Λ_g. Finally, x is the position along the fiber. Note that the phase information $\phi_g(x)$ can be used to 'chirp' the grating, which can be

5   used for dispersion compensation, and also the phase can be used for 'sampling', which produces multiple reflection bands that for example may be matched to the standard ITU grid frequencies used in commercial WDM systems. Phase sampling has been described in detail in U.S. patent application 09/757,386, entitled "EFFICIENT SAMPLED BRAGG GRATINGS FOR WDM APPLICATIONS", which

10   is incorporated herein by reference.

Several methods have been developed for FBG writing using the side illumination of the optical fiber through a phase mask, as illustrated in FIG. 1A (PRIOR ART). Such a typical system includes a source of actinic radiation, for example UV laser

15   100, projecting light along the optical fiber 102 through a phase mask 104. A scanning mechanism 106 may be used for example to illuminate a long section of fiber 102 through the mask 104, typically with a beam of small diameter (a few mm or smaller). Alternatively, one can scan the mask/fiber pair and keep the writing beam fixed, or avoid scanning entirely and use a writing beam large enough to

20   expose the entire section of fiber required. The mask has a periodic structure of grating corrugations 108 on the surface closest to the fiber 102, which, when illuminated by the writing laser, generates diffracted orders forming an intensity fringe pattern that photoinduces a refractive index modulation along the fiber 102, defining the FBG 110.

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The height of the grating corrugations at the mask surface, with peaks and valleys of ±d, has a periodic distribution and can be written as

$$h(x) = d\sin(k_{m0}x + \theta_m(x)) \qquad (2)$$

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where the mask has an underlying period Λ_m and k-vector $k_{m0}=2\pi/\Lambda_m$, and the residual phase of the mask corrugation function is $\theta_m(x)$. Although we assume a sinusoid here for simplicity, typically the corrugation of the mask will be closer to a square wave, but the exact shape does not affect the general concept represented here. The grating corrugations in the mask cause the writing beam to diffract into multiple orders. The corrugation depth $2d$ is chosen such that the $\pm 1^{st}$ orders are maximized and the 0th order is minimized. Typically this depth will be near the size of the UV wavelength (e.g. $2d$ is about 250 nm). For a uniform mask of period Λ_m, the two 1st order beams will interfere to produce an intensity pattern with a fringe period (and thus the period of the grating in the fiber) $\Lambda_g=\Lambda_m/2$. It is also known in the art to use a mask which is patterned with a non-uniform period (chirp) or phase to produce a similarly varying chirp or phase in the FBG. Thus, the phase information is usually embodied into the periodic distribution of the grating corrugations. The amplitude, and therefore apodization, information, however, is usually introduced in the writing process itself. The simplest method is simply to vary the laser beam power during writing. However, this method causes a variation in $n_{eff}(x)$, which leads to severe distortion of the FBG reflection spectrum. To correct this a second pass of fiber exposure is used to equalize $n_{eff}(x)$ over the FBG length, but this is more complex and is subject to various uniformity and alignment issues.

A standard technique to achieve apodization without variation of laser power is by controlled wiggling of the mask during writing, such as for example shown in U.S. patent no. 6,072,926 (COLE et al). This is illustrated in FIG. 1A (PRIOR ART) where mask wiggler 112 is shown. If the mask is wiggled by a distance more than one fringe period, the fringes can wash out completely. By changing the wiggling amplitude one can control the net fringe amplitude and thus control the index modulation amplitude $\Delta n(x)$. This method is still mechanically complex and is subject to the variations of the mechanical wiggling system. Moreover, as a result of nonlinear writing sensitivity, this method can still have the undesired effect of varying the effective average index $n_{eff}(x)$, distorting the FBG spectrum. In the

absence of such a wiggling apparatus, the mask and the fiber can be mechanically joined by a very simple jig (perhaps just a spacer between the fiber and mask and a clamp to hold them together). This type of mechanical arrangement is likely to have the best thermal and mechanical stability, which can greatly improve the

5   quality of the written FBGs.

Ideally, the apodization information should be included in the mask itself, so that the writing process would simply consist of scanning the mask-fiber with the writing laser beam, without additional mechanical variations, or a simple exposure

10   by a stationary large beam.

A few methods have been proposed in the prior art to incorporate the amplitude information into the mask. One approach uses modulation of the duty cycle (i.e. width), or etch depth, of the grating corrugation on the mask to modulate the

15   intensity of the $\pm 1^{st}$ and 0th order diffracted beams, such that the visibility of the fringes in the transmitted light is varied. This approach suffers from a number of practical difficulties in achieving the desired flexibility and accuracy of the amplitude profile, and since the visibility of the fringes is modulated, it is possible that it could generate some undesirable variation of the effective average index of

20   the fiber core, $n_{eff}(x)$. A summary of these prior art methods can be found in the book by R. Kashyap, "Fiber Bragg Gratings", Academic Press, 1999 (chapter 5).

Also known in the art is to use interference between two FBG fringe patterns to control fringe amplitude, as disclosed in U.S. Patent No. 6,307,679 (KASHYAP).

25   However, the two component FBG patterns are written sequentially. As a result, this method has the drawback that the longitudinal position of the fiber must remain very precisely controlled, generally on the scale of 1 nm, between the sequential writing passes of the two FBG patterns. In addition, the writing laser power and beam position and angle must be very precisely maintained between

30   the two writing passes. A number of approaches were also recently proposed in U.S. patent application no. 10/154,505 by Popelek et al, filed on May 24th, 2002

and entitled "Embodying Amplitude Information into Phase Masks", which use a single illumination of the combination of multiple patterns on the same mask to achieve the required apodization.

5   In view of all of the above, there is a need for an improved phase mask and a FBG writing method overcoming the drawbacks of the prior art methods discussed herein.

SUMMARY OF THE INVENTION

10   The present invention therefore provides a Bragg grating photoinduced into a photosensitive medium, the Bragg grating having a light reflection spectrum including a spectral region of interest. The Bragg grating includes a refractive index profile defining grating fringes along the photosensitive medium. The refractive index profile has a periodic apodization phase component, which is

15   designed to apodize the grating fringes reflecting light within the spectral region of interest by generating spurious reflection features outside of the spectral region of interest.

In accordance with another aspect of the present invention there is also provided a

20   phase mask for photoinducing a Bragg grating into a photosensitive medium, the Bragg grating having grating fringes defining a light reflection spectrum including a spectral region of interest.

The phase mask has a plurality of grating corrugations positioned along the mask

25   according to a periodic distribution. This periodic distribution has a periodic apodization phase component. The apodization phase component is designed to apodize the grating fringes reflecting light within the spectral region of interest by generating spurious reflection features in the reflection spectrum outside of the spectral region of interest.

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In accordance with still another aspect of the present invention a method for photoinducing a Bragg grating into a photosensitive medium is provided, the Bragg grating having grating fringes defining a light reflection spectrum including a spectral region of interest. The method includes the steps of:

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a) providing a phase mask having a plurality of grating corrugations positioned therealong according to a periodic distribution, the periodic distribution having a periodic apodization phase component. The apodization phase component is designed to apodize the grating fringes reflecting light within the spectral region of

10   interest by generating spurious reflection features in the reflection spectrum outside of the spectral region of interest;

b) disposing the photosensitive medium along the grating corrugations in close proximity to the phase mask; and

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c) projecting actinic radiation through the phase mask. The actinic radiation is diffracted by the grating corrugations to generate the Bragg grating, this Bragg grating being photoinduced into the photosensitive medium.

20   Finally, there is also provided a system for photoinducing a Bragg grating into a photosensitive medium, this Bragg grating having grating fringes defining a light reflection spectrum including a spectral region of interest.

The system includes a phase mask having a plurality of grating corrugations

25   positioned therealong according to a periodic distribution. The periodic distribution has a periodic apodization phase component. This apodization phase component is designed to apodize the grating fringes reflecting light within the spectral region of interest by generating spurious reflection features in the reflection spectrum outside of the spectral region of interest, the photosensitive medium being

30   disposed along the grating corrugations in close proximity to the phase mask. The system also includes light projection means for projecting actinic radiation through

the phase mask. The actinic radiation is diffracted by the grating corrugations to generate the Bragg grating, the Bragg grating being photoinduced into the photosensitive medium.

5   Stated simply, the present invention enables the use of extremely precise phase-only variations, i.e. the positions of the individual grooves in a phase mask design, to achieve apodization that would otherwise require modulation of the fringe depth in an FBG. This approach has significant advantages over the prior art. First, it allows for fabrication of complex FBGs with a very simple exposure without, for

10   example, the need to use a very small scanned writing beam, or the use of complex mechanical systems such as needed for piezo-driven dithering. The exposure could for example be just a blanket illumination with a stationary large beam. Second, this apodization approach has reduced, if not zero, side effects on varying the average index of the FBG – a problem that can occur with other

15   methods. Finally, this approach has high resolution and mathematical precision, leveraging the precision of semiconductor lithography tools. This enables the manufacture of high resolution and complex FBGs using a precise mask and an extremely simple exposure procedure.

20   Other advantages of the present invention will be better understood upon reading preferred embodiments thereof with reference to the appended drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1A (PRIOR ART) is a schematic representation of a system according to prior

25   art illustrating the standard method for writing an FBG by side illumination through a phase mask; FIGs. 1B and 1C are schematic representations of systems according to preferred embodiments of the present invention.

FIG. 2A is a graph illustrating the effective relative modulation amplitude of FBG

30   fringes resulting from sinusoidal phase only apodization, versus the amplitude of the phase sinusoid according to a preferred embodiment of the present invention;

FIG. 2B is a graph illustrating the transfer amplitude of sinusoidal phase vs spatial frequency according to a preferred embodiment of the present invention.

FIGs. 3A and 3B are graphic representations of the apodization vs position for the
5   phase-only apodization of a single channel linearly chirped grating having an apodization period of 200 µm, according to another preferred embodiment of the present invention.

FIGs. 4A to 4F are graphic representations on two different wavelength scales of
10 the delay, delay difference and spectral amplitude of linearly chirped FBG of FIGs. 3A and 3B.

FIGs. 5, and 5A to 5C show experimental results of reflection spectra for an apodized linearly chirped single channel FBG, the apodization period being about
15 24 µm.

FIGs. 6A to 6C show experimental results for the response, dispersion and group delay ripple for the central channel of the same FBG as in FIG. 5.

20 FIGs. 7A to 7E are graphic representations of the apodization, delay, delay difference and spectral amplitude for a nonlinearly chirped FBG, with an apodization period of 50 µm.

FIGs. 8A to 8E are graphic representations of the apodization, delay, delay
25 difference and spectral amplitude for a nonlinearly chirped FBG, with an apodization period of 25 µm.

FIGs. 9A to 9E are graphic representations of the apodization, delay, delay difference and spectral amplitude for a nonlinearly chirped FBG, with an
30 apodization period of 100 µm.

FIG. 10A (PRIOR ART) is a graphic representation of the periodic phase of a 9-channel phase-only sampled FBG, which generates the uniform 9 central channels; FIG. 10B (PRIOR ART) shows the spectral amplitude of the channels generated by the sampling.

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FIGS. 11A and 11B are graphic representations similar to those of figs 10A and 10B, where phase-only apodization has been added to the FBG, the phase apodization period being of about 25 μm and amplitude of ±2.3856 rad.

10 FIGS. 12A and 12B are graphic representations similar to those of figs 10A and 10B, where phase-only apodization has been added to the FBG, the phase apodization period being of about 25 μm and amplitude of ±2.4046 rad.

FIGs. 13A and 13B are graphic representations of the phase and coupling
15 amplitude for a 41-channel FBG with phase-only sampling and apodization, the apodization phase having a period of about 8.3 μm and an amplitude of ±2.386 rad.

FIGs. 14A and 14B are graphic representations of the apodization vs position for a
20 9-channel linearly chirped phase-only sampled FBG having an apodization period of 25 μm.

FIGs. 15A to 15F are graphic representations, for all channels and the central channel only, of the delay, delay difference and spectral amplitude of the FBG of
25 FIGs. 14A and 14B.

FIGs. 16A and 16B are graphic representations of the apodization vs position for a 41-channel linearly chirped phase-only sampled FBG having an apodization period of about 6.7 μm.

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FIGs. 17A to 17F are graphic representations, for all channels and the central channels only, of the delay, delay difference and spectral amplitude of the FBG of FIGs. 16A and 16B.

5 DESCRIPTION OF PREFERRED EMBODIMENTS OF THE INVENTION

The present invention provides an improvement in the fabrication of fiber Bragg gratings. It relies on the fact that in practice, FBGs are used to modify light beams having a wavelength or wavelengths within a spectral region of interest, the simplest example being the telecommunication C-band. Outside of this region, the

10 reflection features of a FBG are irrelevant. This is advantageously utilized herein to improve their characteristics within the spectral region of interest.

It will be understood that although the description below refers to Fiber Bragg gratings, the present invention could easily be applied to a grating in any

15 appropriate type of photosensitive medium where a refractive index grating is used.

In accordance with the principles of the present invention, there is provided a phase mask for the fabrication of an improved FBG, and the resulting grating

20 photoinduced in an optical fiber. The phase mask includes a plurality of corrugations, positioned so as to have a periodic distribution. This distribution is designed to incorporate in its pattern the amplitude information of the desired FBG. The target amplitude of the grating is here varied by including an apodization component into the location, i.e. the phase, of the corrugations on the mask. This

25 additional phase component is periodic and has an amplitude that varies slowly along the grating. It reduces the local reflectivity along the grating within the spectral region of interest in such a way that the global reflectivity of the grating taken as a whole is as desired within said spectral region of interest. The period of this additional phase component is selected so that spurious reflection features

30 are created outside of the spectral region of interest. In other words, the additional phase component shapes the reflectivity within the spectral region of interest by

creating sidebands outside of said spectral region of interest. As opposed to the prior art methods that vary the diffraction efficiency into the 0th and 1st orders, this method redistributes angularly the UV light within the 1st order in such a way as to vary the amplitude of the grating fringes with periods creating reflectivity within the

5   region of interest, while introducing additional fringes with periods that create reflectivity outside of the spectral region of interest. In this way, one can effectively achieve apodization of the grating fringes relevant to the spectral region of interest, while the actual total fringe amplitude $\Delta n(x)$ is completely constant. Therefore, one substantially eliminates any potential variation in the average index

10    $n_{eff}(x)$, which can result from nonlinear writing sensitivity.

Referring to FIGs. 1B and 1C, there are shown two preferred embodiments of a system 101 to fabricate an FBG, according to another aspect of the present invention. The system includes a phase mask 104 having a plurality of grating

15   corrugations 108 positioned therealong according to a periodic distribution. As explained above, the periodic distribution has an apodization phase component, which is designed to apodize the grating fringes reflecting light within a spectral region of interest by generating spurious reflection features in the reflection spectrum outside of the spectral region of interest. Of course, one skilled in the art

20   will understand that the scale of the grating corrugations with respect to the phase mask, as well as the rate of change of the grating corrugations, have been exaggerated here for illustration purposes only. The optical fiber 102 is disposed along the grating corrugations 108 in close proximity to the phase mask 104. The system 101 also includes a light source 100 for generating actinic radiation, such

25   as but not limited to a UV laser. The light is projected through the phase mask 104. In the embodiment of FIG. 1B, a scanning mechanism 106 is provided to scan the light beam along the length of the mask. In the embodiment of FIG. 1C, shaping optics 107 are provided to enlarge the beam and simultaneously write all of the grating. Of course, additional shaping optics 109 may be added at any point

30   of the light beam's path such as shown in FIG. 1B to modify the light beam as needed, such as for controlling the curvature of the writing beam or focussing the

same on the fiber in the direction perpendicular thereto. The actinic radiation is diffracted by the grating corrugations 108 to generate the Bragg grating 110 by interference of the $\pm 1^{\text{rst}}$ orders, as explained above. The Bragg grating 110 is therefore photoinduced into the optical fiber 102. It should be noted that with a

5   system according to the present embodiment, there is no need for a mask wiggler as shown in FIG. 1A (PRIOR ART), as the amplitude information is directly included in the periodic distribution of the phase mask corrugations.

A practical embodiment of designing the Bragg grating according to a preferred

10 embodiment of the present invention is set out below. It is understood however that the present invention is not limited to the mathematical representation developed here.

Exemplary design of a Bragg grating according to a preferred embodiment

15 **of the invention**

Referring to Eq. (1), the essential idea here is to replace the amplitude function $\Delta n(x)$ by a phase only function. Thus we define a 'phase apodization' function:

$$A(x) = \Delta n_0 \exp[i\phi_{AP}(x)] \tag{3}$$

20

One sees that the function $A(x)$ has a completely uniform amplitude Δn_0, and thus is entirely defined by the apodization phase function $\phi_{AP}(x)$. The goal will be to design $A(x)$ such that it can replace $\Delta n(x)$ in Eq. (1), and the resulting FBG spectrum will achieve the desired performance required for the device in the

25 spectral region of interest. Thus the index modulation, or refractive index profile is written as

$$n(x) = n_{eff} + \text{Re}\{A(x)\exp[i(k_{g0}x + \phi_g(x))]\} = n_{eff} + \Delta n_0 \text{Re}\{\exp[i(k_{g0}x + \phi_g(x) + \phi_{AP}(x))]\}$$

$$\tag{4}$$

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From equation (4) one sees that the index modulation is now a constant Δn_0 and has no amplitude variation whatsoever. The FBG could then be written with an appropriate phase mask that incorporates both the usual designed grating phase $\phi_g(x)$ (e.g. chirp etc) and the proposed apodization phase $\phi_{AP}(x)$, and thereby no modulation of the actual fringe amplitude would be required, either through wiggling of the phase mask or by other methods.

In accordance with a preferred embodiment of the present invention, $\phi_{AP}(x)$ is set equal to a rapidly varying sinusoid whose amplitude is slowly varying, in comparison to the period of the sinusoid, as a function of x. The sinusoid is selected here as it is a particularly simple embodiment to analyze, but it is understood that the present invention could also be applied using any other relevant periodic function. The sinusoidal phase variation causes the FBG fringes that reflect within the spectral range of interest to disappear, partially or completely, while generating spurious fringes that reflect at a period well out of the spectral range of interest. Put another way, a periodic phase variation will cause generation of harmonic sideband channels in the reflection spectrum. These spurious 'apodization' sideband channels are generated at the expense of reducing the reflection response in the central channel of interest. That is, the sinusoidal phase modulation effectively reduces the reflectivity in the central channel, or equivalently reduces the effective amplitude of the grating responsible for the reflectivity of the central channel.

Thus, one defines the apodization phase as

$$\phi_{AP}(x) = \phi_0(x)\sin(2\pi x / P_A) \tag{5}$$

where the amplitude of the sinusoid $\phi_0(x)$ varies slowly in comparison to the sinusoid period P_A. To understand how this method works, first consider this

phase apodization as used with a uniform grating of wavenumber k_{g0}. That is, let the FBG modulation be given by

$$n(x) = n_{eff} + \Delta n_0 \, \text{Re}\{\exp[i(k_{g0}x + \phi_{AP}(x))]\} \qquad (6)$$

5

Now one makes use of the identity

$$\exp[i\phi_0 \sin(\theta)] = \sum_{m=-\infty}^{\infty} J_m(\phi_0) \exp[im\theta] \qquad (7)$$

10   where J_m is an ordinary Bessel function. One takes $\theta = 2\pi x/P_A$ to obtain

$$n(x) = n_{eff} + \sum_{m=-\infty}^{\infty} \Delta n_0 J_m(\phi_0(x)) \, \text{Re}\{\exp[i(k_{g0}x + m2\pi x/P_A)]\} \qquad (8)$$

The index modulation can then be viewed as resulting from a superposition of
15   gratings, each with an index modulation profile $\Delta n_0 J_m(\phi_0(x))$ and a k-vector $k_{g0} + 2m\pi/P_A$. The central wavelength ν_m of the grating with subscript m in the series thus verifies the following equation, i.e.

$$n_{eff}(\nu_m)\nu_m = \frac{c}{4\pi}\left(k_{g0} + \frac{2m\pi}{P_A}\right). \qquad (9)$$

20   The frequency separation between the individual reflectivity spectra can be calculated as follows. According to equation (9),

$$n_{eff}(\nu_{m+1})\nu_{m+1} - n_{eff}(\nu_m)\nu_m = \frac{c}{2P_A}. \qquad (10)$$

25   On the other hand, the effective group index n_g is defined as (G. P. Agrawal, Nonlinear fiber optics 2nd Ed., Academic Press, 1995)

$$n_g = n_{eff} + v \frac{dn_{eff}}{dv} \; . \tag{11}$$

The effective group index thus verifies the following equation, i.e.

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$$n_g dv = d(vn_{eff}) \; . \tag{12}$$

Equation (10) can thus be rewritten as

$$n_g \Delta v = \frac{c}{2P_A} \; , \tag{13}$$

10

where Δv represents the frequency spacing between neighbouring reflectivity spectra of individual gratings. For example, if P_A = 100 µm, the frequency spacing between the individual reflectivity spectra Δv is about 1000 GHz corresponding to 8 nm in wavelength shift at 1550 nm.

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The reflectivity spectrum of the phase-apodized grating described by equation (6) is given by the combination of the reflectivity spectra of the individual gratings in the series in equation (8) as long as these reflectivity spectra do not overlap spectrally. In other words, the reflectivity spectrum of the phase-apodized grating

20   will be given by the combination of the reflectivity spectra of the individual gratings appearing in the series in equation (8) as long as these gratings do not interfere with one another. To this end, the frequency spacing Δv calculated above must be large enough. Also, the individual spectra must be narrow enough. This second condition puts a limit on the speed at which the amplitude $\phi_0(x)$ of the apodisation

25   phase component can vary along the grating. As aforementioned, the amplitude of the index modulation associated to an individual grating is given by $\Delta n_0 J_m(\phi_0(x))$. A rapidly varying amplitude $\phi_0(x)$ will produce a broadening of the reflectivity spectra of the individual gratings that could lead to interference between the gratings.

This representation of the phase-apodized grating as a superposition of gratings is a mathematical view that helps understanding the behaviour of these phase-apodized grating. It will however be understood that this should not be interpreted to mean that the phase-apodized grating is fabricated by superposing gratings. As

5   a matter of fact, the preferred embodiments decribed herein do not use such a fabrication technique, but photoinduce the grating through a scan of a small beam or exposure with a large beam of a phase mask which includes the elements of the invention in its design. Moreover, it should be realized that the series in equation (8) contains an infinite number of terms: the phase-apodized grating

10   cannot in principle be fabricated by writing superposed gratings. Even if the number of individual gratings was finite, it would be exceedingly difficult to fabricate the phase-apodized grating by superposing individual gratings, since this superposition should be performed with a well defined phase relationship between the gratings.

15

The mathematical representation of the phase-apodized grating as a superposition of individual gratings with different central frequencies is especially useful when the individual gratings do not interfere with one another. Under this condition, only the central grating ($m=0$) provides reflectivity in a spectral region of interest, and

20   the spurious apodization gratings ($m \neq 0$) can therefore be ignored. This leaves a central channel as would be reflected by a uniform grating, with an equivalent amplitude as a function of the position x along the fiber given by

$$\Delta n(x) = \Delta n_0 J_0 (\phi_0 (x)) \tag{14}$$

25   or

$$\phi_0 (x) = J_0^{-1} (\Delta n(x) / \Delta n_0) \tag{15}$$

where Δn_0 is the maximum grating amplitude when the phase apodization ϕ_0 is zero. Thus, the effective reduction in $\Delta n / \Delta n_0$ is given by the 0th order Bessel function J_0, which is plotted in Fig. 2A. One sees that the reduction of Δn varies

30   smoothly with ϕ_0 until Δn reaches zero at the first zero of J_0, for $\phi_0 = 2.4048$. Thus

one can fully control the apodization by designing $\phi_0(x)$ to precisely vary between 0 and 2.4048.

To summarize the above reasoning more concisely, if one desires to write the grating with index modulation

$$n(x) = n_{eff} + \mathrm{Re}\{\Delta n(x)\exp[i(k_{g0}x + \phi_g(x))]\} \qquad (16)$$

one can instead write a grating with no amplitude variation along the length $\Delta n(x)$, i.e. a grating with constant fringe amplitude Δn_0 and "phase-only" apodization as in Eq. (4)

$$n(x) = n_{eff} + \Delta n_0 \,\mathrm{Re}\{\exp[i(k_{g0}x + \phi_g(x) + \phi_0(x)\sin(2\pi x / P_A))]\} \qquad (17)$$

where $\phi_0(x)$ is given by Eq. (15). P_A is required to be sufficiently small such that the spurious sidebands at $\Delta v_m = mc/2n_g P_A$ are of no concern, and that the scale of the variation in $\phi_0(x)$ is long compared with P_A.

Phase mask design according to a preferred embodiment

To obtain a grating having the refractive index profile defined above, the phase mask used for its fabrication must have an appropriately designed grating corrugation distribution.

Fabrication of FBGs with complex and high frequency phase patterns using a mask is discussed at length in U.S. patent no. 6,654,521 (SHENG et al). A standard arrangement used for FBG side writing, with the fiber proximal to the mask may be utilized. One may scan a writing beam as shown in FIG. 1B, or a large stationary beam may be used to expose the entire required section of the FBG, as shown in FIG. 1C. As disclosed by SHENG, it is preferable to account for the diffraction from the mask to the core of the fiber to properly design the mask to

achieve the desired phase variation in the FBG. These diffraction effects are more easily compensated if one minimizes the distance between the mask and the fiber. Herein below, the essential results are summarized, and the application to the phase-only apodization method is described. It should be understood that this

5   approach is a simple approximation used to illustrate an exemplary embodiment of the présent invention, and that a more sophisticated diffraction analysis (e.g. propagation of plane wave spectra, or vector diffraction) may be needed for some mask-fiber spacings and grating designs.

10   It is desired to write an FBG with phase for apodization given by Eq. (5) and repeated here

$$\phi_{AP}(x) = \phi_0(x)\sin(2\pi x f_A) \tag{18}$$

15   where $f_A = 1/P_A$ is the spatial frequency of the apodization sinusoid. Because the $\pm 1^{st}$ order diffracted beams, which interfere to form the FBG, meet the fiber core at a distance Δz away from the mask, and are incident at an angle θ_0 away from normal incidence, they come from slightly displaced positions $x = \pm \Delta x/2$ at the mask, where Δx is defined by the diffraction angle θ_0 and the mask-fiber spacing

20   (see FIG. 1 and Eq. (14) of U.S. patent no. 6,654,521). If one describes the phase of the mask corrugation by $\theta_m(x)$, then it was shown in U.S. patent no. 6,654,521 that the phase of the grating in the core of the fiber is given by

$$\phi_{FBG}(x) = \theta_m(x - \Delta x/2) + \theta_m(x + \Delta x/2) \tag{19}$$

25

Taking the Fourier transform, one obtains the phase frequency transfer function for the mask-to-fiber writing process:

$$\tilde{\phi}_{FBG}(f) = 2\cos(\pi f \Delta x)\tilde{\theta}_m(f) \tag{20}$$

30

where $\tilde{\phi}_{FBG}$ and $\tilde{\theta}_m$ are Fourier transforms and f is the spatial frequency of the mask or FBG phase. Thus, in the case of apodization with a sinusoidal phase as defined in Eq. (18), one designs the mask to have an apodization phase (in addition to any other phase components designed for chirp or sampling) with a

5 sinusoidal component defined by

$$\theta_{AP}(x) = \theta_{AP0}(x)\sin(2\pi x f_A) \tag{21}$$

where the appropriate mask phase amplitude $\theta_{AP0}(x)$ is designed to account for

10 diffraction, and can be found using Eqs. (18) and (20):

$$\theta_{AP0}(x) = \phi_0(x)/2\cos(\pi f_A \Delta x) \tag{22}$$

To achieve robust manufacturing with this technique, it is desirable to have a

15 maximum tolerance to changes in the fiber-mask distance. Variations in this distance cause a change in Δx and thus would alter the effective amplitude of the sinusoidal phase in the grating. Differentiation of the relationship (22) gives the incremental change in the phase amplitude for an incremental change $\delta(\Delta x)$ in the value of Δx

20

$$\delta\phi_0(x) = -2\pi f_A \theta_{AP0}(x)\sin(\pi f_A \Delta x)\delta(\Delta x) \tag{23}$$

Thus, to achieve the greatest tolerance to changes in Δx one sees that it is desirable to minimize f_A, however this may not be possible since for some designs

25 f_A must be sufficiently large to resolve rapid changes in apodization and to avoid interference from multiple channels. For large f_A, one can still achieve good tolerance by choosing f_A such that the sinusoid in Eq. (23) is zero, i.e. when $f_A\Delta x = q$, q an integer. As an example, if the mask-fiber distance is of about 10 μm, then one finds that Δx is of about 25 μm, and the sin factor will be zero for $f_A =$

30 1/25, 2/25, or 3/25 μm^{-1}, etc, or equivalently P_A= 25, 12.5, or 8.3 μm, etc (since

$P_A=\Delta x/m$). In FIG. 2B the transfer amplitude, that is eq. (20) normalized to unity, is plotted for the case where $\Delta x=$ 25 μm, and the spatial frequency has been scaled in terms of the frequency shift of the apodization channels in units of 100 GHz intervals (i.e. $(cf_A/2n_g)/100$ GHz). Thus, for example an apodization period of 25

5   μm would correspond to a shift of about forty 100 GHz channels. From FIG. 2B one sees that the transfer amplitude has extrema at about 40, 80, 120, 160 channels. At these extrema one has zero derivative, as per Eq. (23) and thus maximum tolerance to changes in the mask to fiber distance. However, from inspection of Eqs. (22) and (23), one can see that the higher order extrema at

10 larger f_A still have increased sensitivity to changes in Δx. It would therefore be preferable to operate at the first extremum (40 channels in this example), however taking into consideration that f_A must still be large enough such that undesirable interference effects do not limit the FBG performance. As shown below, for 40+ channel designs, the required value of $cf_A/2n_g$ may be as large as about 16 THz

15 (160 channels). In this case one must ensure greater mechanical stability such that the changes in Δx are minimized.

Exemplary experimental results of Bragg gratings according to preferred embodiments

20 The use of the principles represented by Eqs. (17) and (15) has been tested on sample FBG designs. In all of the designs considered here, the conventionally required FBG apodization $\Delta n(x)$ is obtained by Fourier synthesis. This approach assumes that the reflectivity spectrum of a FBG is given by the Fourier transform of the refractive index modulation profile of said FBG. This approach is valid as

25 long as the reflectivity of the FBG is small. This is done for simplicity and numerical convenience only. For more complex designs, such as those with high reflectivity spectra, a more sophisticated design method, such as inverse scattering techniques (see e.g. "Feced et al, J. Quantum Electron. Vol. 35, p1105-1115, 1999), could be used to determine $\Delta n(x)$. Then, one could apply Eq. (15)

30 using $\Delta n(x)$ found by such a design method to obtain $\phi_0(x)$ and generate a phase-

only apodized grating as described by Eq. (17). Indeed, any method may be used to design a desired apodization profile $\Delta n(x)$ and then Eq. (15) may be used to define a phase-only apodized grating using Eq. (17).

5   FIGs. 3A, 3B and 4A to 4F show the result of phase-only apodization for a simple linearly chirped single channel FBG with 1000 ps/nm dispersion. The period of the apodization sinusoid is chosen to be 200 μm, so that the spurious apodization channels are separated by about 4 nm (500 GHz) from the desired dispersion compensation channel. FIG. 3A shows the desired and effectively achieved

10   apodization profile by varying of $\phi_0(x)$, as determined by Eqs. (14) and (15). FIG. 3B shows the actual amplitude variation assumed for $\Delta n(x)$. It can be seen from FIG. 3B that $\Delta n(x)$ is taken to be constant over the entire active region of the grating, which is arbitrarily taken to be the length over which the effective amplitude $\Delta n(x)$ is greater than 2×10^{-4} of the peak, but it is reduced to zero at the

15   ends of the region to eliminate spurious reflection that could result from the abrupt change at the end. If suppression of the end reflection is needed, then the transition at the grating ends can be essentially of any form so long as the transition is not too rapid. In the case of FIG. 3B, there are no adverse effects for end transition regions wider than about a few 100 μm. As a result, a number of

20   prior-art techniques could be used to incorporate the end transitions into the mask, since they are not critical. One method is just a gradual reduction of the width or depth of the mask grooves over the transition region. In general, one would expect that for larger spectral separation of the spurious apodization channels, the termination of the grating ends should be less critical. The 'end' apodization is

25   included in the simulations here for numerical convenience only, and is not a required aspect of the invention. However, it is possible that it may be beneficial in some grating designs. As will be noted below, the experimental results indicate that such grating end apodization is not necessary to achieve excellent results, at least for the dispersive grating design used in this measurement.

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FIG. 4A shows the calculated group delay (solid) compared to the desired linear variation (dashed), and FIG. 4B shows the difference between the desired and calculated delays. FIG. 4C shows the calculated reflectivity amplitude of the phase-only apodized grating. It can be seen that over the ~0.4 nm bandpass of the reflective channel, there is no discernable difference between the desired and calculated group delay (i.e. zero group delay ripple), thus demonstrating the phase-only apodization method works as desired.

FIGs. 4D to 4F show the same calculation as for figs 4A to 4C on a wide bandwidth scale, so that one can observe the spurious 'apodization channels'. It can be seen that these channels have separation of ~ 4 nm (500 GHz) as one would expect from the apodization period P_A = 200 μm. Note also, as seen in FIG. 4F, that each of the spurious channels is peaked near its spectral edges, and the response in the center of each spurious channel is near zero. This is simply a result of the redistribution caused by the phase-only apodization method. The apodization does not reduce the reflectivity at the center of the desired channel and so does not induce reflectivity at the center of the spurious channels. However, the apodization does reduce the reflectivity at the edges of the desired channel, by redistributing it at the edges of the spurious channels. Mathematically, this behavior stems from the fact that the amplitude of the gratings associated with the spurious channels is given by higher order Bessel functions, as seen in Eq. (8).

As mentioned earlier, with $P_A \leq 25$ μm, one would obtain a separation of more than 32 nm, exceeding the entire width of the telecommunications C-band. Such an experimental result, using a phase-only apodized, linearly-chirped FBG of dispersion of about -1500 ps/nm, is shown in FIG. 5. The apodization period P_A is of about 24 μm. One sees that the frequency separation of the spurious channels is about 4.3 THz (or about 35 nm, an interval corresponding to some 43 channels separated by 100 GHz). The structure of the spurious channels, as seen in the enlargements of peaks FIGs. 5A to 5C, is exactly as predicted in FIG. 4F, with a

minimum at the spurious channel center and the reflectivity peaked near the spurious channel edges. The desired central channel shows a smooth reflectivity with no significant side lobes and the noise floor outside the channel is more than 30 dB down from the peak. FIGs. 6A, 6B abd 6C show the measured response,

5   dispersion and group delay ripple of the central channel. One observes very small group delay ripple, less than 8 ps peak-to-peak. This is another indication that the apodization method is achieving excellent results. It should be emphasized that this experimental result was obtained without any additional apodization (by means other than the designed phase-only method) of the grating ends

10   whatsoever. This demonstrates that phase-only apodization alone may be used to fabricate dispersion compensating FBGs with excellent spectral characteristics.

FIGs. 7A to 7E and 8A to 8E show calculations of phase-only apodization of nonlinearly chirped single channel gratings. For FIGs. 7A to 7E the apodization

15   period is 50 μm, and the dispersion varies linearly over the channel bandwidth according to $D=(-500\ ps/nm)+(800\ ps/nm^2)\Delta\lambda$. In FIGs. 8A to 8E the apodization period is 25 μm, and the dispersion is $D=(-30\ ps/nm)+(2000\ ps/nm^2)\Delta\lambda$. The plots are similar to those above, but FIGs. 7A and 8A show the desired and achieved apodization profiles on a linear scale, whereas FIGs. 7B and 8B show the desired

20   apodization (dashed) and actual constant $\Delta n(x)$, with tapers at the ends, on a log scale.

Note that in FIGs. 8A and 8B the target apodization profile has very dramatic oscillations from maximum to near zero, and thus is a rigorous test of the phase-

25   only apodization method. In FIGs. 7D and 8D one sees again that the group delay is indistinguishable from the desired quadratic over the central portion of the reflectivity channel. As mentioned, the apodization period used is 25 μm in the case of FIGs. 8A to 8E, but if one increases this period, one starts to observe errors in the calculated spectrum. This effect is shown in FIGs. 9A to 9E, which is

30   the same grating design as in FIGs. 8A to 8E, except that the phase apodization period has been taken as 100 μm. Modest but significant group delay errors can

be seen in the channel center as well as amplitude error in the wings of the reflectivity. This appears to result from the rapid oscillations in the desired apodization profile. The phase modulation amplitude $\phi_0(x)$ can no longer be considered to vary slowly over a period P_A of the apodization. This rapidly varying

5   amplitude $\phi_0(x)$ produces a widening of the spurious sidebands that now overlap with the central channel. In order to eliminate this interference, it is then necessary to move the spurious sidebands further away from the spectral region of interest by shortening the period P_A of the phase apodisation. If the apodization period cannot be reduced, the phase profile $\phi_0(x)$ can be designed with a different

10   approach than prescribed by Eq. (15). For example, a nonlinear optimization iterative process can be used, such as the simulated thermal annealing, simplex, Gerchberg-Saxton, and other optimization methods described in U.S. patent no. 6,654,521 and U.S. patent application 09/757,386, whereby the complex reflectivity spectrum is calculated at each iteration and the phase profile $\phi_0(x)$

15   and/or the underlying grating phase $\phi_g(x)$ is varied until the desired complex reflectivity is achieved to a desired level of accuracy.

As discussed in previous U.S. patent no. 6,654,521 and U.S. patent application 09/757,386, a periodic phase included in the grating design can be used to

20   "sample" the FBG and thereby generate a series of periodically spaced channels that can be adapted for use in a commercial WDM system. FIGs. 10A and 10B respectively show such a periodic phase that has been designed to generate 9 uniform channels, and the spectral amplitude of the channels generated by the sampling. The uniformity of the 9 central channels is better than 1%, but many

25   unused 'extra' channels are also generated. The phase apodization method may be used in conjunction with the "phase sampling" to reduce the amplitude of all 9 of these channels by adding a periodic apodization phase of sufficiently high frequency such that the spurious 'apodization channels' are adequately spaced away from the desired central 9 channels, and therefore do not cause noticeable

30   interference. Thus one would have an index modulation given by

$$n(x) = n_{eff} + \Delta n_0 \, \text{Re}\{\exp[i(k_{g0}x + \phi_g(x) + \phi_{Samp}(x) + \phi_0(x)\sin(2\pi x / P_A))]\} \quad (24)$$

where $\phi_{Samp}(x)$ is the periodic sampling phase, and $\phi_g(x)$ is the underlying phase corresponding to the chirp common to all the channels. The period of $\phi_{Samp}(x)$,

5   P_{Samp} determines the spacing of the central channels according to $\Delta\nu_{Samp} = c/2n_g P_{Samp}$. For example, if the sampling period is about 1.03 mm, then the channel spacing $\Delta\nu$ is about 100 GHz, a standard ITU spacing for WDM channels. Phase-only apodization of a 9 channel spectrum generated by the phase of FIG. 10A and according to Eq. (24) is demonstrated in FIGs. 11A, 11B, 12A and 12B,

10   where the apodization phase amplitude is applied as per Eq. (15). The apodization phase amplitude is set to $\phi_0 = 2.386$ rad for FIGs. 11A and 11B and $\phi_0 = 2.4046$ rad for FIGs. 12A and 12B, so as to reduce the amplitude of the central 9 channels to 10^{-2} and 10^{-4} of the maximum, respectively. The phase apodization is seen to impact equally on all 9 channels. Note that as the amplitude is decreased, the

15   interference from the unwanted channels in the wings generated from the spurious 'apodization channels' becomes more of an issue. This constrains the apodization frequency to be large enough so that this potential overlap is not significant. In this case, the apodization period $P_A \sim 25$ μm corresponds to a 40 channel (at 100 GHz spacing or 4 THz) shift of the apodization channels, which is seen to be adequate

20   to obtain good uniformity of the 9 channels at the 10^{-4} level. As one increases the channel count of the desired central band, then the apodization period will need to be decreased to ensure adequate separation between the desired channels and the spurious apodization channels.

25   An example of this characteristic is shown in FIGs. 13A and 13B, for a 41 channel phase-only sampled grating apodized to a target level of 10^{-2}. The phase apodization applied is uniform with amplitude $\phi_0 = 2.386$ rad and period $P_A = 8.3$ μm, corresponding to a shift of the apodization channels of about 124 channels (12.4 THz). Because this shift is insufficient, one observes significant nonuniformity (>

30   30%) in the amplitude of the center 41 channels, owing to interference from the

spurious apodization channels. Simulations (see FIGs. 16A, 16B and 17A to 17F) show that a shift of about 154 channels (15.4 THz frequency shift, or apodization period $P_A \sim 6.7$ μm) is sufficient to achieve adequate uniformity.

5   In the above calculations for 9 and 41 channel sampled gratings of FIGs. 10A to 13B, $\phi_g(x)$ is taken to be zero and one obtains identical channels each originating from a uniform grating, and thus only the overall channel amplitudes are plotted. If instead $\phi_g(x)$ is chosen to give a linear chirp, i.e. a quadratic phase, then one obtains a multi-channel grating with equal dispersion in each channel. An example
10   of this is shown in FIGs. 14A, 14B and 15A to 15F, where $\phi_g(x)$ is chosen to correspond to a dispersion of D=1000 ps/nm. It can be seen that 9 uniform channels with identical linear group delay are obtained. The deviation of the group delay from the desired linear design is seen to be negligible in the single channel plot of FIG. 15E. Here again the apodization period selected is P_A = 25 μm (40
15   channel shift), which is seen to be adequate to ensure good uniformity and negligible group delay ripple in each of the desired channels.

Similar calculations are shown in FIGs. 16A, 16B and 17A to 17F, but in this case the phase-only sampling is designed for 41 central channels. As a result, a much
20   larger offset for the spurious apodization channels is required to avoid interference between channels, and thus undesirable non-uniformity and group delay ripple. Therefore, an apodization period of P_A~6.7 μm is used in these calculations, which corresponds to an apodization frequency of about 15.4 THz or an offset of about 154 channels. From the above-referred figures one sees that the apodization with
25   a 15.4 THz offset is sufficient to ensure good uniformity and negligible group delay ripple in each of the desired channels.

In summary, a sinusoidal phase component is applied to a phase mask in order to precisely control the apodization characteristics of the photoinduced FBG. The
30   phase modification is periodical but does not necessarily need to be sinusoidal. The present invention therefore provides a method to control the apodization

amplitude of the channel(s) of interest by a phase-only modification to the FBG and/or mask. This approach requires that the reduction of apodization and reflectivity in the channel(s) of interest be accompanied by a redistribution of reflectivity to another spectral region, which by design should be of no concern.

5

It should be noted that the analysis of sinusoidal phase apodization and its implementation in the mask is based on the approximate relationship found between the mask and fiber phase and disclosed in U.S. patent no. 6,654,521, as described above in Eqs. (19) and (20). In practice this approximation may be

10 inadequate, especially for higher apodization frequencies, where a more complete diffraction analysis is required. However, regardless of the analytic method, one can always perform an experimental calibration of the effective apodization obtained as a function of the periodic (perhaps sinusoidal) apodization phase amplitude. Such a calibration would then replace the analytic result of Eq. (22), or

15 some more sophisticated diffraction calculation. The experimental calibration curve obtained would then replace FIG. 2A, and an empirically calibrated, modified version of Eq. (15) could then be used to design $\phi_0(x)$ and thus the mask for any given desired apodization profile, in a manner similar to that described by Eqs (14) to (17). In addition, the phase modulation for apodization and the phase of the

20 underlying grating design may be optimized to achieve the desired apodization and FBG spectral response by a number of well known techniques, such as those described to optimize the sampling spectrum in U.S. patent no. 6,654,521 and U.S. patent application 09/757,386.

25 It may also be beneficial to combine the proposed technique with prior art concepts such as variations of the mask groove depth or duty ratio along the length of the grating. This approach may be helpful at the very ends of the grating, where some type of amplitude apodization may be helpful in avoiding spurious FBG reflections owing to the abrupt end of the phase apodization. It should be

30 emphasized that apodization of the grating ends by a means other than phase-

only apodization is not a required aspect of the invention, but may be beneficial in some circumstances.

Of course, numerous changes or modifications could be made to the embodiments
5   above without departing from the scope of the present invention as defined in the appended claims.